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Chapter

Real-Time Communication Protocols for IoT and Wireless Sensor Networks: A Short Survey

Valentin Stangaciu

Abstract

Researchers in the real-time systems field have been focusing mainly on transferring the real-time principles to new technologies such as Internet of Things or Industry 4.0. Most of their contribution was made in aspects regarding sensing, environment monitoring, resource management, and scheduling, while the field of communication protocols received less attention. In the case of Internet of Things or wireless sensor networks, real-time support should not only be provided at a local or node level, but also at the whole system level including the communication layers. This implies that the whole network should communicate with respect to application defined time constraints. In order to achieve this goal, even the components of the network nodes need to function in a timely manner. This chapter will address the state of the art regarding real-time communication protocols for different layers with focus on real-time aspects for Internet of Things, regarding both inter- and intra-node communication. The study will identify the current research gaps and propose future research directions and approaches.

Keywords: real-time communication, Internet of Things, wireless sensor networks, communication protocols, protocol stack

1. Introduction

Wireless sensor networks (WSNs) refer to a mature technology that provides the means for the implementation of various types of applications, which are now almost indispensable in many fields. In very simple and general terms, a WSN is represented by a significant number of low-power devices with wired or wireless communication capabilities that handle sophisticated monitoring and control tasks usually on medium or large areas. These devices are characterized by having few computational and storage resources and are mostly battery powered [1].

The newly emerged concept known as Internet of Things can be seen as an enhancement or an upgrade of the already existing WSN platforms [2]. In the IoT terminology, the classical WSNs are integrated in the Edge Layer while adding crucial functionality in the Fog and Cloud Layers. Such enhancements greatly increase the usability of the classical WSNs by providing better integration and exposing their potential in many other fields.

One important area of applicability for WSNs is represented by real-time applications. In such applications, the system should not only provide accurate results but it must function within strictly defined time constraints. The real-time capabilities of WSNs, and later applied to IoT networks, have been of great interest to both researchers and industry; thus, these are crucial in time critical application. Real-time aspects have been studied on many levels of IoT networks and WSNs such as operating systems, sensing, or control. However, the communication between the nodes of the WSN at the Edge Layer of IoT did not receive the needed research attention.

This chapter aims at providing an objective analysis regarding the current state-of-the-art of the communication protocols used in WSN in the Edge Layer of IoT mainly from a real-time perspective. The outcome of this study is to identify the current gaps in the available literature regarding real-time communication protocols for IoT Edge Layer and to also provide relevant research directions in this field. This work aims to address both intra-node and inter-node communication solutions thus providing a support study for much more complex node architectures.

2. Research questions and methodology

The purpose of this section is to briefly describe how the study presented in this chapter was conducted, by identifying the research questions used to analyze this work.

2.1 Research questions

This work is based on the following research questions and its main goal is to provide the appropriate answers with proper justification: (Q1) What are the main use cases for WSNs and IoT? (Q2) Is there a clear need in using such networks in time-critical applications? (Q3) Is real-time supported in IoT networks? (Q4) At what IoT layer is real-time suited best? (Q5) Is there any real-time support available at node level? (Q6) Is there any real-time support for communication? (Q7) What communication protocols are used and what is the degree of real-time support? (Q8) What are the open issues and challenges regarding the real-time support of IoT networks from a communication perspective?

2.2 Data source

The research articles that were used in this study were collected from many international databases such as IEEE (IEEE Explore), Elsevier (Science Direct), ACM Digital Library, Springer Nature, MDPI.

2.3 Search criteria and keywords

This study analyzed around 160 publications from the past 5 years with only some notable exceptions where the references were older than 2019 but were properly justified to enter the study. The fundamental keywords that were used to select the publications that were included in this study are mainly the following: Internet of Things, wireless sensor networks, communication protocols in Internet of Things Edge, communication protocols in wireless sensor networks, real-time communication in Internet of Things, real-time communication in wireless sensor networks, communication protocol stacks in Internet of Things and wireless sensor networks, ZigBee, CoAP, MQTT, MQTT-SN ZWave, Lora, and Matter Communication Protocol.

3. Related studies

The IoT revolutionary paradigm received significant attention during the past few years; thus, great advances were made in this domain. Such advances were concentrated in many literature surveys and reviews, which provide good insights regarding many aspects of this domain. A selection of the most recent surveys in this field is summarized in **Table 1**.

Most of the studies focus on the applicability and structure of IoT in many fields thus emphasizing their impact on common daily activities such as healthcare [5], agriculture [3], artificial intelligence-related applications [6], or general environment monitoring and control applications [4].

A crucial aspect of IoT networks is represented by communication between the components not only at Edge Layer but also regarding the Fog and Cloud Layers of IoT. There are many stable communication solutions available for all the layers of IoT which are constantly being updated to adapt for the new arising challenges [7]. Many of the literature studies regarding the communication protocols applied in IoT are either focused on general aspects [8, 10] or are targeted on specific protocols or protocol stacks such as MQTT or WirelessHART [9].

Other important studies are introducing the use of artificial intelligence and machine learning into some aspects of design, implementation, or operation of communication protocols [11, 13, 14] and even at MAC level [12] while also analyzing concerning security aspects [15, 16].

Far fewer contributions were made in the crucial and particular type of IoT networks represented by critical real-time IoT networks. While real time, in the context of IoT, is mentioned by few studies [18, 19], real-time communication protocols are rarely addressed. Giving the latest expansion of IoT and WSNs in many new fields, communication was studied for more particular applications such as for UAV [24] or vehicular *ad hoc* networks [23] especially at a MAC level.

Reference	IoT app	AI ML	IoT security	Comm protocols	Real time	Real time communication
[3–6]	✓					
[7–10]	✓			✓		
[11]	✓	✓				
[12]		✓		✓		
[13, 14]	✓	✓	✓	✓		
[15–17]			✓	✓		
[18]					✓	
[19]				✓	✓	
[20–24]				✓	✓	✓
This study	✓			✓	✓	✓

Table 1.
Comparison table of current existing studies.

A much more general study is presented by the authors [22] where a thorough analysis is conducted regarding the real-time MAC protocols suitable for IoT and WSNs. An objective summary of the existing real-time protocols is presented in Ref. [21] emphasizing the status in field as it settled in 2017. Most of the existing studies that take the real-time aspect into account usually present only research prototypes and do not provide any off-the-shelf solutions that can be easily integrated into an IoT network. The most objective justification in this statement is that such solutions are not actually available at such level or have very limited availability.

A much more comprehensive and recent study is presented by the authors in Ref. [20] from an industrial point of view but with significant applicability in other various domains.

The study presented in this chapter intends to extend most of the related work described in this section by adding the latest research results in the field of real-time communication in IoT. Furthermore, this work also analyses real-time communication at a node level for more complex applications where multi-layered node architecture comes into attention.

4. Internet of Things and wireless sensor networks

Defined by the British scientist Kevin Ashton in 1999, the Internet of Things concept aims to connect various types of devices to the Internet, thus creating a network of objects, with the main purpose of providing monitoring and control services for a large area of applications. This concept divides the functionalities into three layers: an Edge Layer represented by the actual small interconnected devices that provide the main monitoring and control functionalities, and a Fog Layer for implementing the management and interconnectivity of the Edge Layer for interfacing it with the Cloud Layer which is mainly responsible for the user interface and storage, analysis, and prediction of data [25].

During the last decade, the number of various designs of Internet of Things systems that have been built or studied increased almost exponentially contributing to the development and advancement of many fields. The Internet of Things concept was used to design specialized platforms for many fields such as medical and healthcare [26–28], smart home and smart city [29–31], industrial or environment monitoring, and control applications [32–34] and even in academic education for improving the knowledge of students in cybersecurity for IoT [35].

As it can be easily observed and according to many researchers in this field [36, 37], the key component of the Internet of Things concept is represented by the classical wireless sensor networks. Such networks represent the Edge Layer of IoT entirely and also provide the integration with the Fog Layer. Considering such an approach it is clear that all the WSN-related studies and concepts are applicable for IoT networks.

This section will further discuss architectural aspects regarding WSNs in IoT Networks in Section 4.1, with a detailed description of node level architectures in Section 4.2 but with particular applicability in the real time domain in Section 4.3.

4.1 Background and architecture aspects

A wireless sensor network consists of a large number of intelligent sensing devices, called nodes, mobile or fixed, which are located in a building or disposed over an exterior open surface, with wireless communication capabilities, which through collaborative actions form a sensor network with the role of implementing a specific application as an autonomous system.

The most important functionalities within a WSN are represented by sensing and communication. In terms of communications, as it can be observed in **Figure 1**, there are two main network topologies. The AD-HOC topology describes a network organization where the nodes are dynamically deployed without a defined strict hierarchy and without the need of a network coordinator. Such networks, as depicted in **Figure 1a**, do not have a predetermined and fixed topology; thus, they are usually self-organizing and the communication pathways are extremely dynamical [38]. Even though these networks are extremely dynamical, scalable, and suitable for mobile network nodes, their main disadvantage is that the communication protocols have an increased complexity, which may affect power effectiveness.

On the other hand, many existing solutions are based on a cluster network topology. In such a case, the network is organized in a hierarchy topology where the whole network is coordinated by a special node designated as a Network Head (NH). The network is then divided into cluster each being managed by a cluster head (CH) as described in **Figure 1b**. The main disadvantage of such networks is that they are not as dynamic as the *ad hoc* networks and they need special dedicated nodes to serve as NH or CH [39]. However, such network topologies offer a higher degree of predictability and less complex communication protocols.

As stated earlier in this chapter, WSNs provided the foundations for the IoT concept. From an architectural point of view, the IoT paradigm is organized into three basic layers as presented in **Figure 2**. The Edge Layer is represented by various WSNs which provides the implementation of the main raw functionality of the system mainly related to monitoring and control. Communication is implemented using WSN specific communication protocols. These WSNs are coordinated by the devices in the Fog Layer, which have the role not only to manage and coordinate the networks but also act as sinks or data concentrators. The Fog Layer can also be considered as the gateway between the Edge Layer and the upper Cloud Layer, which offers functionalities such as user interface for the whole system as well as data storage, analysis, and prediction. The data exchange between the Fog Layer and the Cloud Layer is usually handled by Internet protocols.

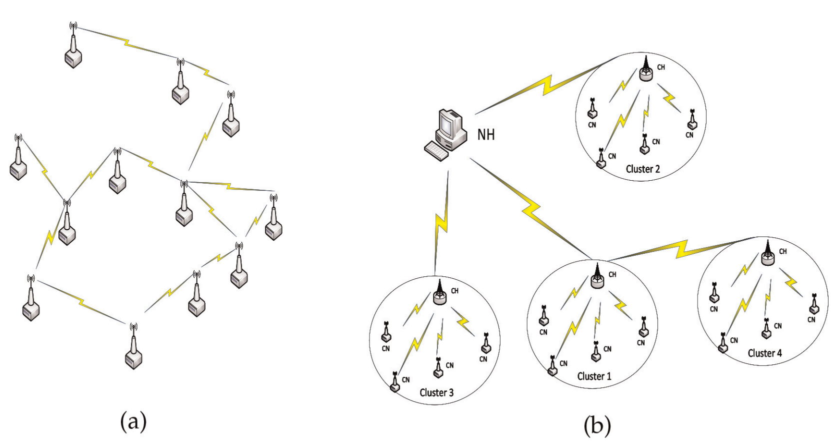

Figure 1.
Wireless sensor network topology. (a) AD-HOC network topology. (b) Cluster network topology.

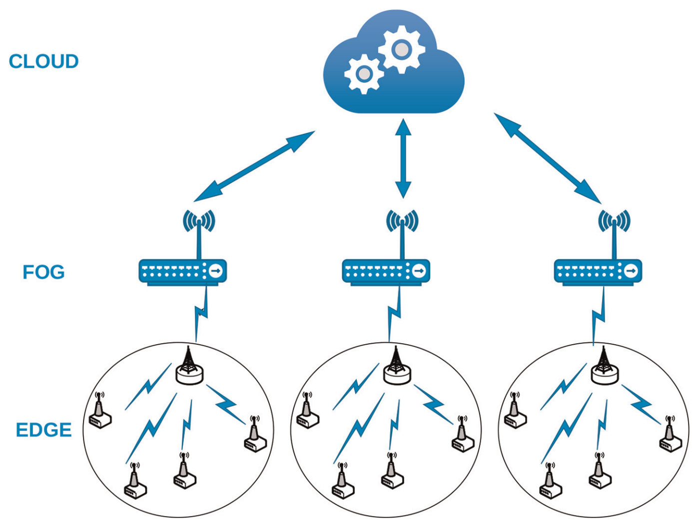

Figure 2.
IoT Edge-Fog-Cloud architecture.

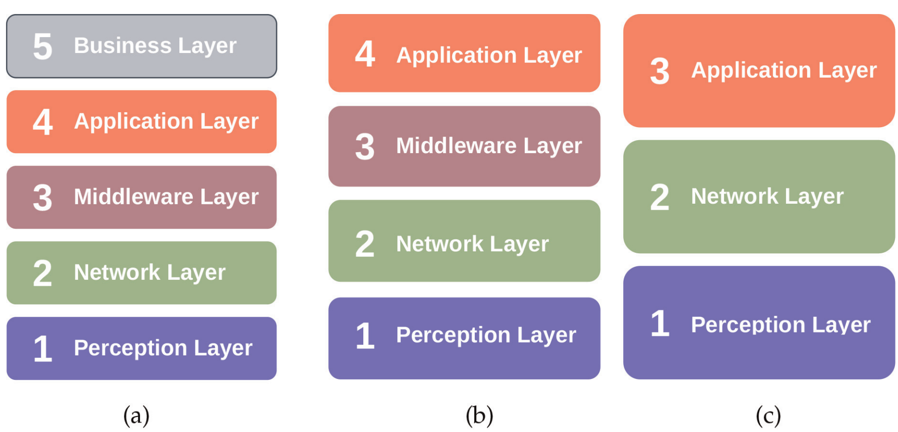

Figure 3.
Internet of Things architectures. (a) Five-layer architecture. (b) Four-layer architecture. (c) Three-layer architecture.

On the other hand, from a functional point of view, the IoT concept is structured differently and was subject to some important changes throughout the evolution of IoT systems. In a very close relation to the Edge-Fog-Cloud organization, researches firstly defined the three layered architecture as presented in **Figure 3c**. In such an organization, the *Perception Layer* is responsible for the environment monitor and control and is implemented by the sensing and control functionalities of the WSN nodes in the Edge Layer. The *Network Layer* provides the communication between the nodes and also offers interfacing with the upper layers. The *Application Layer* has the role to implement the main overall functionality of the IoT system and to also provide data storage and analysis to the user along with the user interface [14].

Such a trivial architecture, as the one in **Figure 3c**, would be in a tight relation with the Edge-Fog-Cloud organization: The *Perception Layer* is clearly handled by the *Edge*

Layer, while the *Fog Layer* implements the communication protocols and interfaces of the *Network Layer* leaving the *Application Layer* to be managed usually be the *Cloud Layer*. Naturally, in this three layered architecture, all the data obtained by the *Perception Layer* would be transferred to the *Application Layer* using the communication services provided by the *Network Layer*.

An improvement of this architecture is made when adding an additional layer between the *Network Layer* and the *Application Layer* denominated as the *Middleware Layer* which introduces the ability of the system to preprocess, filter, and storage of intermediate collected data before sending it to the *Application Layer*. The addition of the *Middleware Layer* [40] relieves the Cloud Layer of unnecessary data processing and storage by transferring such operations to the Fog Layer thus also decreasing network traffic. Such a solution resulted into adding further complexity to the architecture of IoT as depicted in **Figure 3b**.

The final version of the Internet of Things architecture as presented in **Figure 3a** introduces another important layer, which intends to provide administrators and analysts means to have an overview of the system's functionalities in order to monitor the system but to also configure it at any level.

4.2 Node-level architectures

The main component of a WSN is the sensor node which is usually implemented by a small embedded system with communication and sensing capabilities. The node is usually battery powered, and has low computational and memory resources. The central component of a node is represented by a microcontroller, which runs a small memory footprint firmware. The software implements the communication and sensing drivers along with a trivial application that provides the means for the node to be integrated into the whole network offering its sensing capabilities.

In most cases such simple node architecture would suffice; thus, WSNs have a large number of nodes with different sensing or control capabilities. However, in much more complex applications such a simple approach may be insufficient. Such complex application are represented by collaborative robotic platforms [41], node-level heterogeneous networks where nodes may be equipped with different submodules depending on the application requirements, real-time critical applications, or where a single CPU would be insufficient to manage all the processes within a node.

A solution presented in this chapter is a multi-modular, plug'n'play node architecture where the node's functionalities are distributed across autonomous submodules.

Such a concept of a complex node is presented in **Figure 4** where the complex node is divided into multiple submodules, each being autonomous and having its own CPU. The central submodule that manages the node's entire behavior is represented by the *Main processing* module.

This main module along with the *Inter-node communication* module, handling the communication with the rest of the WSN, and the *Power management* module providing the power for the whole node are mandatory in such a configuration, while other modules may be connected as needed by the application. Moreover, the *Power management* module may also be responsible for the battery management (i.e., battery monitoring, charging, and battery life expectancy analysis).

In such a configuration, depending on the application, the node may be equipped with other specialized modules such as: a *Mobility* module, an *Imaging* module for video acquisition, an *Orientation* module to provide directions, and distance

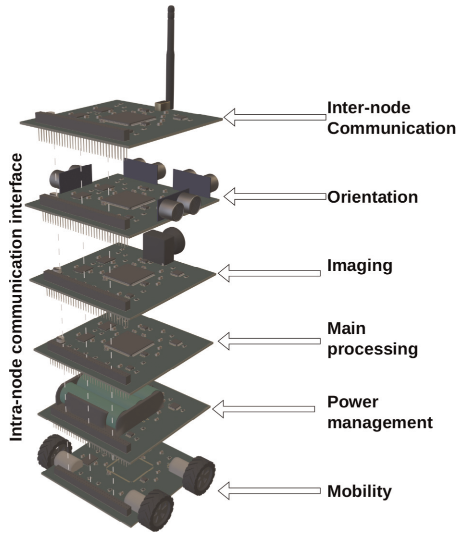

Figure 4.
Complex sensor node.

measurement in case mobility is involved or other modules to handle various sensing capabilities.

This architecture considers that each module of the complex sensor node is autonomous and has its own CPU, which handles the basic sensing, movement, or control functions specific to each module. Each module is connected to a common *Intra-node communication interface*. This bus is therefore managed by the *Main processing* module to implement the communication between the rest of modules within the node. Using specific communication protocols, the *Main processing* module uses this bus in order to configure the node's modules, to transfer data as well as to detect new modules added to the node.

Such architecture could pose important challenges; thus, it practically represents a multi-processor system adapted for a node of an Internet of Things network.

4.3 Real-time aspects

A real-time system is a special type of system where time is a crucial parameter. In such systems, a correct operation is not only dependent on the logical result provided by the system but also on the physical amount of time taken by the system to produce the result [42]. Real-time systems are used to implement time critical applications where time constraints need to be applied in order for the application to achieve its goal.

The most important time parameters that are used to define the time constraints of an application or task are the following: release time—the moment in time when the task becomes available for execution, the deadline—the absolute moment in time until the execution of a task must be completed, response time—the period between the time when the task is ready to be executed and the time it finishes its job execution and the Worst Case Execution Time (WCET)—the maximum amount of time taken for the task to be executed in the worst possible scenario.

Depending on how the time constraints defined above are applied, there may be three types of real-time systems: Hard Real-Time (HRT) Systems—when meeting the deadlines is critical and failing them may lead to catastrophic system failure, Firm Real-Time (FRT) Systems—when failing the deadlines may produce erroneous results and will affect the stability of the system, and Soft Real-Time (SRT)—when failing the deadlines may only impact the performance of the system.

In the case of IoT, real-time constraints may only be applied at Edge Layer and at the connectivity between the Edge Layer and the Fog Layer. Given that IoT Cloud Layers are connected to Fog Layers using Internet-specific communication protocols, the concept of real time cannot be applied to these layers because there is no support for real time and predictability of Internet protocols.

In order for IoT systems to serve time critical applications, the Edge Layer must support real-time constraints. Such a feature is clearly possible considering that this layer is mainly represented by WSNs that, during the last decades, were applied in many such applications. For such a goal to be achieved, the entire Edge Layer must function in a real-time manner. Communication between IoT nodes, communication between IoT nodes, and the Fog Layer gateways and node functionality must all support strict time constraints in order to provide a system wide real-time operation.

At node level, the real-time support is ensured by a Real-Time Operating System (RTOS). One very popular solution in this case is FreeRTOS [43], which received significant scientific attention due to its high level of support and availability for a great number of hardware platforms that allowed other projects to extend its capabilities [44]. Other solutions intend to offer similar real-time support such as ContikiOS [45], RIOT designed especially for IoT [46], TizenRT [47], or even GNU/Linux-based operating system with real-time extensions such as LitmusRT [48] or the newly emerged Kernel extension—sched_ext Extensible Scheduler Class [49]. Many of such operating systems, growing along with the IoT domain, in order to adapt to the needs of the applications, begin to offer new real-time task scheduling support for Mixed Criticality Systems where tasks may have different levels of criticality [50].

When dealing with more complex node architecture as the one specified in Section 4.2 in **Figure 4**, all the components of the node need to function in a real-time manner. This implies that real time must also be applied at intra-node commutation thus using communication protocols and communication protocol stacks able to perform in a real-time manner.

5. Intra-node communication protocols

Intra-node communication protocols are defined as the protocols used to implement communication within various submodules of a WSN or IoT sensor node in a complex node architecture. In such an architecture, the node may be considered a multi-processor system thus each sub-module is autonomous having its own CPU. The aim of such communication protocols is to provide a stable communication between these submodules.

Even if the complexity of IoT networks is increasing, multilayered complex node architectures are rarely used; thus, few intra-node communication solution is currently available or studied. An important exception to this claim is related to the automotive industry where intra-system communication protocols are used inside vehicles that may be easily adapted for IoT nodes. Such protocols are usually built upon the CAN interface such as the DiveCAN protocol [51].

In order to implement intra-node communication, standard interfaces such as I2C or SPI are used as basis; thus, many CPUs already have hardware support for the physical layer and are deterministic, which facilitate the implementation of real-time communication. Few such solutions are available or studies, and most of them provide only limited support for some needed OSI layered. However, solutions such as TinyI2C [52, 53] or SPI-related protocols [54, 55] offer a starting point for further study and development, while other full stack solutions such as PARSECS_RT [56] concentrate on a predictable real-time communication.

On the other hand, studies have been made to build intra-node communication protocols without making use of existing PHY layer implementation, thus providing totally new solutions better adapted for sensor nodes focusing on one-wire communication such as SENSIBUS [57].

6. Inter-node communication in Internet of Things

Inter-node communication is much more studied and developed in WSNs or IoT networks; thus, many full stack solutions are currently available to implement communication between nodes in the Edge Layer and Fog Layer. Researches usually focus on studying or improving certain stack layers with respect to the OSI Reference Model [58]. In real time, in order for a full communication stack to provide a time-constrained communication, predictability must be provided at each layer of communication.

The protocol layer having the most impact in terms of performance or real-time behavior is represented by the physical Layer which is at the base of the OSI Model providing the MAC basis for communication. Having this in mind, protocols related to this layer receive most of the researcher's attention. Studies of these protocols are made on different directions such as energy efficiency [59] or improving communication throughput and predictability for time critical systems [60–64]. Furthermore, MAC protocols were studied in order to improve communication in specific areas such as UAV [65], Smart Home [66], or healthcare [67].

While studying existing literature in this domain, it easy to observe new applicability domains of WSNs or IoT Networks that generate improvements of not only sensing devices but also in terms of communications. Such an example would be represented by underwater environments where MAC communication protocols are adapted to fit the needs of such applications thus greatly improving physical layer protocols [68–70]. Another important aspect worth mentioning is the integration of artificial intelligence and machine learning techniques into analyzing, evaluating, extending, and developing extensions for existing protocols [71].

Beside MAC protocols, a significant impact over IoT communication is given by the application layer protocols. Such protocols depend on the lower layers and offer the means to encode the transferred data or commands [72] in order to implement application functionalities.

One of the most popular application layer protocol in IoT is MQTT, which has a very good software support and is integrated in a lot of existing IoT applications. MQTT requires a central component (MQTT Broker) to manage the entire network and uses TCP/IP as the transport protocol stack. This requirement limits its usage to IoT nodes that have significant amount of hardware resources and are capable to implement the TCP/IP stack over either Ethernet or Wi-Fi. Even so, because of its robustness and scalability, MQTT is widely studied and continuously improved mostly regarding security enhancements [73–77].

Another similar application layer protocol is CoAP [78, 79], which depends on UDP as a transport protocol having the same disadvantage as MQTT by not being able to be used on small devices low on hardware resources. Protocols such as MQTT or CoAP do not offer support for time critical real-time system; thus, they rely on non-deterministic communication protocol stacks.

A much more suitable solution for small devices and with great potential to be used in time critical systems [80] is represented by the MQTT-SN protocol. Being a smaller version of MQTT, MQTT-SN is adapted to be used in sensor networks without the need of a strict transport protocol which facilitated its usage in many WSN applications [81, 82] using low-rate wireless interfaces. Currently, there are many aspects left uncovered about the MQTT-SN protocol; thus, many research aspects may be coined into feasible projects.

In many IoT projects, application designers and developers easily choose wireless interfaces that provide full stack communication. One of the most popular and mature communication protocol stack is the ZigBee stack [83]. This technology currently provides a standardized and viable solution of implementing communication in IoT Edge Layer for various types of applications such as Home Automation [84] or environment [85] and in-door [86] monitoring and even in critical applications [87]. A strong and important competition for ZigBee is represented by Z-Wave providing similar functionality for implementing the IoT Edge Layer communication [88, 89]. The main disadvantage of such solutions is their limited ability to be integrated into real-time critical applications.

On the other hand, such disadvantages can be overcome by using a more industrial approach such as WirelessHART [90]. This solution offers a full stack implementation for wireless communication for industrial sensor network. Being built on top of the IEEE 802.15.4 standard, WirelessHART concentrates on using the Guaranteed Time-Slot mechanism provided by this standard to implement a predictable communication [91] with some improvements provided by the scientific community regarding this property [92]. The main disadvantage of this promising technology is mainly represented by the extremely low availability for modules and devices to be integrated into IoT projects; thus, few producers offer market solutions in comparison with ZigBee modules market availability.

With higher availability, LoRa technology integration in IoT networks is increasing. Such energy-efficient technologies [93] offer communication solutions for many areas of IoT application, especially in agriculture and environment monitoring [94, 95] with significant improvements by using artificial intelligence and machine learning [96].

7. Discussions and research directions

Communication in Internet of Things still poses a challenge for implementing various types of applications especially those that require strict time constraints for time critical domains. Even if there are important mature solutions to implement communication at Edge Layer, researchers still try to improve this aspect of IoT networks.

Considering the brief analysis provided by this chapter, the following research directions and challenges may be identified:

- *Complex node architectures:* When dealing with more complex applications, simple node architectures based on a single CPU, sensors, and a communication interface may not be enough. Much more complex architectures could be proposed using multiple CPUs in order to give more functionality to a sensor node

- *Intra-node communication protocols:* Giving the lack of such protocols, new protocols could be designed in order to provide stable and time-bounded communication between components within a sensor node.

- *Wireless real-time communication protocols:* In order to provide real-time support to time critical applications, IoT networks need to also provide time-bounded and predictable communication at Edge Layer. Researchers must focus on studying real-time MAC protocols; thus, such protocols have the most powerful impact over wireless communication.

- *Studying and integrating WirelessHART into more IoT implementations:* WirelessHART is used in only limited implementation; thus, its potential should be studied on a large variety of applications.

- *Using machine learning and artificial intelligence:* Communication protocol analysis using machine learning techniques could identify important improvements for Edge Layer communication.

- *Using mobile nodes in IoT networks:* Researchers could also focus on implementing IoT networks with enhanced node mobility; thus, many current applications involve only static nodes.

8. Conclusions

This chapter aims to present current and recent studies regarding communication protocols at Edge Layer. Furthermore, a more complex node architecture is discussed in order to attach more functionality to simple sensor node. The most important and popular communication solutions for IoT are identified while emphasizing potential improvements in the direction of real-time processing for IoT networks as well as time-bounded and predictable communication at Edge Layer.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

WSN	wireless sensor networks
IoT	Internet of Things
MAC	medium access control
CoAP	constrained applications protocol
MQTT	message queuing telemetry transport

MQTT-SN	message queuing telemetry transport for sensor networks
IoT App	Internet of Things applications
AI	artificial intelligence
ML	machine learning
RTOS	real-time operating system
UAV	unmanned aerial vehicle
NH	network head
CH	cluster head
HRT	hard real-time
SRT	soft real-time
FRT	firm real-time
MCS	mixed criticality system

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